

# Construction of a Soil Chronosequence Using the Thickness of Pedogenic Carbonate Coatings

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## ABSTRACT

A soil chronosequence is a quantitative description of how the properties of soils in a given area change with time. Chronosequences are important for several reasons, including their use as a tool for dating Quaternary landforms such as stream terraces, and should be included in earth-science education. An excellent index of soil age is the thickness of pedogenic calcium-carbonate coatings on the bottoms of pebbles in gravelly soils. Coating thickness is a simple and quantitative soil property and thus is particularly useful for educational purposes. We develop the general subject by constructing a soil chronosequence for the Lost River Valley of Idaho using this index. Reproducibility analysis indicates that, the mean of thickness measurements of coatings from the carbonate soil horizon should be accurate to within 10 or 20%. The coatings have thickened through the Holocene and latest Pleistocene, but short-term thickening rates have varied between  $1.1 \text{ to } 0.4 \text{ mm/10 ky}$ . Long term rates are  $6 \pm 1 \times 10^{-3} \text{ mm/y}$ .

**Keywords:** Geochronology; surficial geology - soils.

## scope

Soils are complex environmental systems, and soil scientists often write only for technical audiences. For these reasons, it can be difficult for educators to incorporate the subject of soils into their curricula. The purpose of this paper is to provide educators and students with a simple and complete example of a soil chronosequence. The quantitative index of soil age used is simply the thickness of pedogenic calcium-carbonate coatings on the bottoms of pebbles in gravelly soils. Anyone can make the measurement and it does not require expensive equipment.

The value of this paper to the educator is twofold. First, a big school or college lecture can be prepared on the subject using the text for background information and the figures as examples. In addition to the general idea that soils change through time, other concepts can be incorporated, including the importance of reproducible measurements, the use of stratigraphic and crosscutting relationships to establish relative age, and numerical - ("absolute") age determination. Although our result is a geochronology tool specific to our study area, pedogenic calcium-carbonate coatings on the bottoms of pebbles are commonly found

in soils throughout arid regions of the western United States. Therefore, this paper can be used as background for developing a field exercise to determine the relative ages of stream terraces in your backyard. If the soils in your area do not contain pedogenic carbonate, weathering rinds on stones is an alternative criterion and Birkeland (1984) discusses it and other soil properties that are dependent on time.

After an introduction to the subject, the discussion below follows the steps for developing a chronosequence: 1) familiarizing oneself with the study site and local soils, 2) choosing a time-dependent soil property, 3) verifying the reliability or reproducibility of that property's measurement, and 4) incorporating numerical-age constraints into the chronosequence. We conclude by illustrating the usefulness of the chronosequence.

## Introduction

Soils change with time, and, therefore, it is possible to estimate the age of a soil by analyzing its degree of development. The age of a soil is the time elapsed since it started to develop, and it is also the age of the host deposit if it has remained stable. Depositional landforms, such as stream terraces, are stable if sedimentation stops and erosion does not subsequently alter the deposit or its surface. Properties of soils on stable surfaces change progressively and predictably with time. This allows the scientist to study soils on landforms that are similar but have different ages in order to develop a chronosequence, which is a quantitative description of how the properties of soils in a given area change with time (Birkeland, 1990). After a chronosequence is defined, it can be used to determine the relative ages of nearby soils of unknown age. In addition, accurate estimates of soil age and rates of soil formation can be determined if numerical-age constraints can be incorporated into the chronosequence. Numerical-age constraints include radiocarbon ( $^{14}\text{C}$ ) isotopic ages of charcoal that can be shown in the field to predate or postdate a deposit and its soil.

Chronosequences are important for three reasons. First, they can help our understanding of the very processes that form soils (for example, see Chadwick and others, 1990). Next, they can be used as a tool to correlate and date stream terraces formed by regional climate change (for example, see Bull, 1991). Lastly, they can be used to establish the age of local events, such as a prehistoric faulting that ruptured stream terraces (for example, see Machette, 1978).

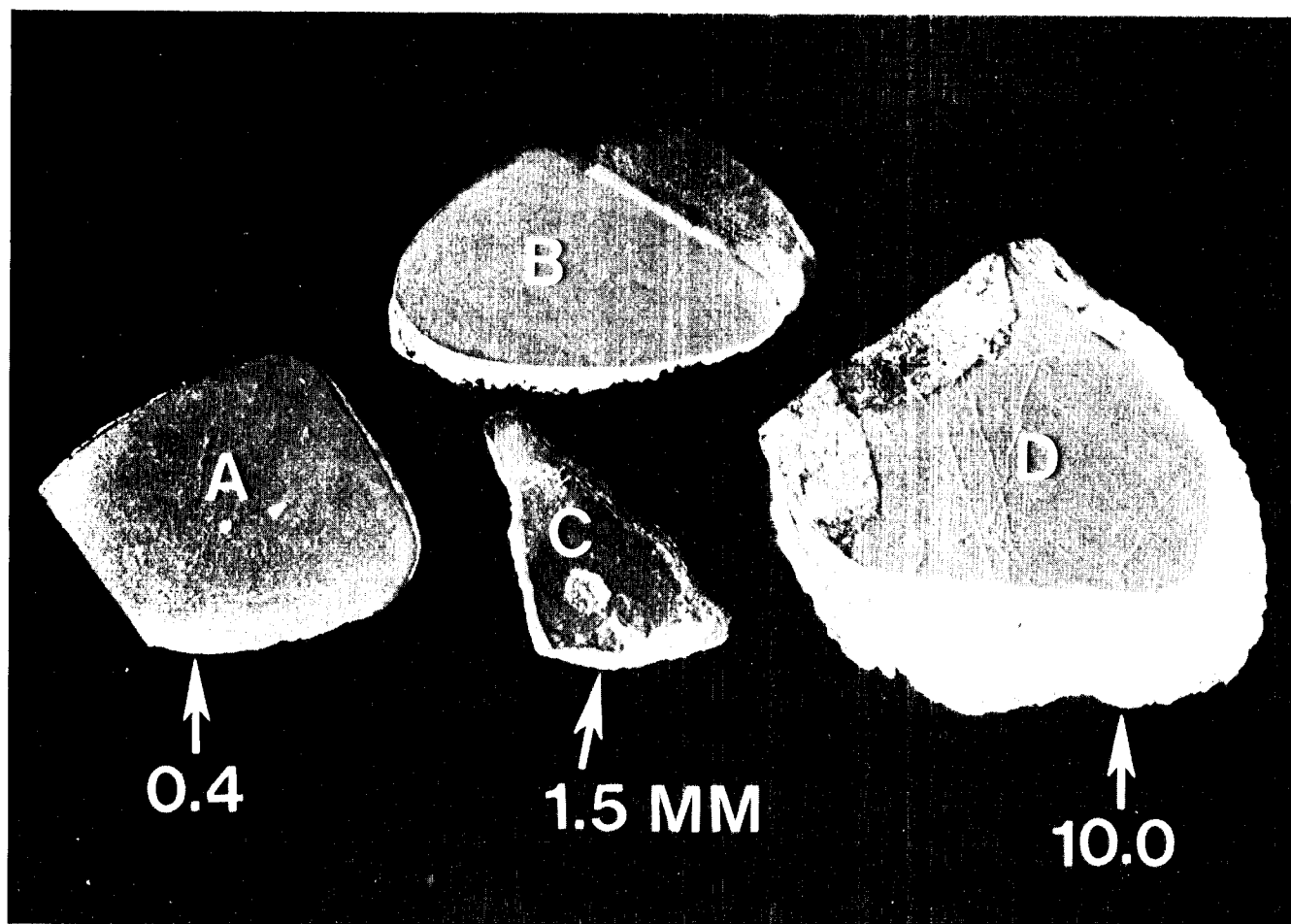


Figure 1. Photograph of pebbles with calcium carbonate coatings from soils of differing age. Sample A is from a soil less than 1,000 years old. Samples B and C are from a soil about 18,000 years old, and sample D is from a soil more than 100,000 years old. The thickness of laminar coatings (labeled in millimeters) are measured where the coatings are the thickest. Thicknesses should be measured where the coating surface is smooth and internal laminations are parallel to the contact of coating and pebble. Coatings should be avoided if they have bumps or pendants like the coatings on sample B or on the left side of sample D.

Specific soil properties depend not only on time, but also on local climate, vegetation, topography and the parent material (Jenny, 1941; Birkeland, 1984). Important factors of the parent material, stream deposits in this case, include the lithology and sizes of sediment particles. Consequently, if the objective is to build a chronosequence, the scientist must select those soil properties most dependent on time and restrict their study to soils that have the same vegetation and parent material, for example. In addition, a chronosequence may be simple or complicated because soils in different regions may have a few or many time-dependent properties. At some locations, for example, an index of soil development might need to be constructed using several properties such as soil color, clay content, and soil structure (Harden, 1982). But properties like color or structure are challenging to quantify. In the semi-arid environment of Idaho, however, the thickness of calcium-carbonate coatings on pebbles from within the soil (Figure 1) is the single most useful property, and it is easy to quantify (Pierce and Scott, 1982).

#### Study Site

Our study area is the Lost River Valley of east-central Idaho. This elongate graben is bounded on the northeast by the Lost River Range; both were formed during the past six million years by normal faulting along the active Lost River fault (Scott and others, 1985). The altitude at the base of the mountain is about 2,100 m, and the alpine summits rise above 3,700 m. Bedrock is mainly Precambrian and Paleozoic dolomites, limestones, and quartzites. The alluvial valley contains the Lost River and its late Quaternary river terraces, but it is dominated by alluvial fans shed from the adjacent mountains at various times during the Quaternary (Scott, 1982). The alluvial surfaces support cold-desert vegetation dominated by sage brush (*Artemisia tridentata*) and bunch grasses. Mean annual temperature in the area is about 3°C, and mean annual precipitation is approximately 25 cm.

The study sites are all located close to the Lost River fault and between Lower Cedar Creek (near the town of Mackay) and Willow Creek (Double-Spring

Pass Road). The two principal sites are at Elkhorn Creek and Rock Creek, but data from other sites are also incorporated into this discussion. The stream names and geographic coordinates mentioned here can be located on the following USGS topographic maps: Dickey Peak, Borah Peak, Elkhorn Creek, and Mackay quadrangles.

### Character of the Study Soils

The study soils are developed in Holocene stream-terrace and debris-flow deposits, and latest Pleistocene alluvial fans and glacial moraines. All deposits are gravelly with pebbles and cobbles occupying 30 to 75% of the volume (Vincent and Chadwick, 1994). Most of the sand and gravel particles consist of dolomite and limestone, and most of the deposits are capped by a thin (<20 cm) deposit of eolian dust. Temporal changes in soil color, texture, and structure are not pronounced. The prominent characteristic of the study soils is the presence of secondary calcium carbonate, which is often called pedogenic carbonate or caliche.

Throughout the semi-arid regions of western North America, horizons with calcium carbonate ( $\text{CaCO}_3$ ) commonly develop in soils (Machette, 1985). Calcium can enter the soil in solution with rain or snow water, it can dissolve within the soil from limestone or dolomite, or it can weather from silicate minerals such as plagioclase. The source of oxygen in pedogenic carbonate is water, and the source of carbon is atmospheric  $\text{CO}_2$  that enters the soil through plants (Quade and others, 1989). As infiltrating water moves down through the soil profile, three processes (at least) can cause the soil water to become saturated with these elements initiating the precipitation of calcium carbonate (McFadden and others, 1991). First, students might benefit from knowing that calcium carbonate is the dominant compound in the evaporite deposits (scale) that form in water heaters and tea kettles. In addition, the deposition of scale in a tea kettle is a good analogy for two of the processes that cause: precipitation of calcium carbonate in soils. Boiling of tea water results in evaporation of water and thus concentration of ions in solution, and ultimately this loss of water volume can lead to super saturation and precipitation of calcium carbonate. In soils, water loss results from direct evaporation from the soil but, more importantly, from the uptake of soil water by plant roots and transpiration of that water through plant leaves. Two other processes rely on the factors that influence the volatility of the compound in water. Volatility is the saturation point or maximum concentration of ions in solution before precipitation occurs, and for calcium carbonate the volatility in water is influenced by temperature and carbon dioxide ( $\text{CO}_2$ ) content. Carbon dioxide is more soluble in cold water than warm water, meaning cold water can hold more of the constituents of calcium carbonate. Thus, when water is heated, the volatility is decreased and calcium carbonate can precipitate even

if there is no water loss. Soils experience an annual cycle of temperature change, although this may not be the most important process of deposition of calcium carbonate. The influence of  $\text{CO}_2$  on solubility, however, is very important. Plants respire  $\text{CO}_2$  through their roots, and thus the concentration of  $\text{CO}_2$  in soil air and water changes with the annual cycle of plant productivity. Since the calcium-carbonate volatility in water increases with  $\text{CO}_2$  content, soil water can become saturated and precipitate calcium carbonate when plants become less productive. Soil microorganisms can also be important in the precipitation of calcium carbonate (Klappa, 1979; Phillips and others, 1987). The factors that limit pedogenic calcium carbonate appear to be the source of calcium and the availability of moisture (Machette, 1985). If there is too much moisture, however, the elements will be flushed from the profile, explaining why pedogenic carbonate is not found in soils of humid lands.

Early during soil development, calcium carbonate precipitates onto soil particles, then it proceeds to occupy pore space, and ultimately it dilates the soil with formation of a massive and nearly pure horizon of "talc" etc" (Gile and others, 1966; Bachman and Machette, 1977; Reheis and others, 1992). Pedogenic carbonate precipitates on sand and silt, but this can be quantified only with difficulty (Reheis and others, 1992). If the sediments are gravelly, however, the early stages of soil development are characterized by tile forming of calcium-carbonate coatings on the bottoms of pebbles (Figure 1). The thicknesses of these coatings are easy to measure. Calcium-carbonate development has not progressed beyond pebble-bottom coatings in the Idaho soils discussed here.

The thickness of these coatings increases with time (Figure 1), but several factors produce variability. Like most soil properties, the thickness of pebble-bottom coatings changes with depth (Figure 2). In addition, carbonate coatings on stones from a single horizon do not all have the same thickness (Figure 2). Both measurement techniques and natural variability must be addressed when building a chronosequence.

### Measurement of Coating Thickness

The use of carbonate-coating thickness as an index of soil age was pioneered in Idaho by Pierce and Scott (1982) and Pierce (1985). The actual measurement of the thickness of a coating is relatively simple; all one has to do is break the stone in half, find the thickest coating with laminated macrostructure, and measure its thickness. For research purposes, coating thickness is measured with a comparator - an inexpensive, hand-held optical device with slight magnification and a scaled reticle that is placed on the object being measured. The finest graduation of the scale is 0.05 mm. For educational purposes, coatings can be measured with a see-through ruler and a hand lens. Carbonate coatings exhibit a variety of growth forms or macrostructures (Figure 1), but measurements of thickness should be restricted to laminated (parallel-layered) coatings or structureless

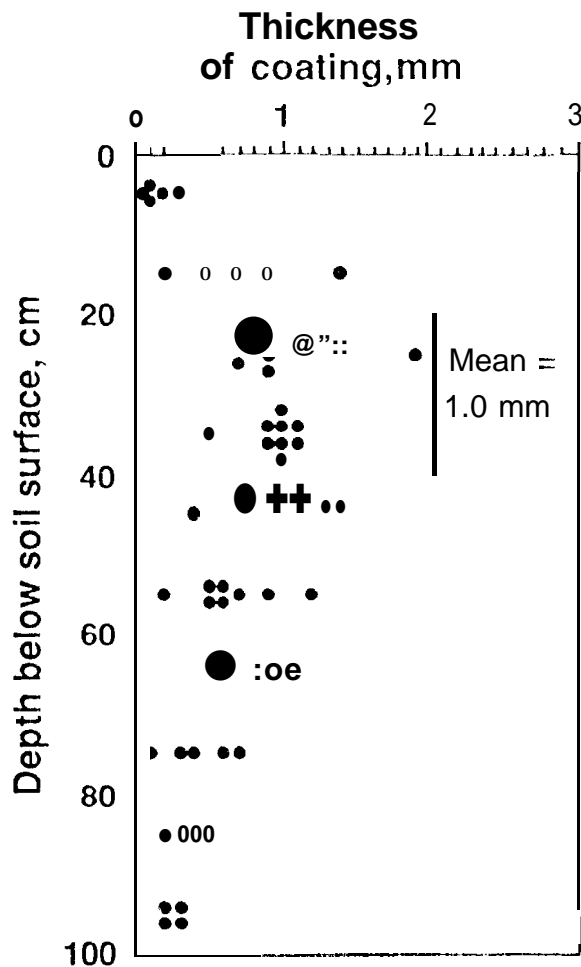


Figure 2. Soil profile showing the thickness of individual pedogenic calcium-carbonate pebble-bottom coatings as a function of depth below the soil surface. The index of soil age used in this study is the mean thickness of pebble-bottom coatings from the 20-cm thick horizon of maximum carbonate accumulation. In this example 1.0 mm is the mean of the samples from the 20-40 cm depth interval.

coatings with smooth surfaces that are parallel to the contact of coating and pebble.

Since the thicknesses of pedogenic carbonate coatings vary with depth in the soil (Figure 2), Pierce (1985, p. 197) measured the "thickness of laminated calcium-carbonate coats from the undersides of limestone clasts collected from a depth in the soil where coats are the thickest." Because coatings on pebbles from a single horizon do not have precisely the same thickness, he averaged the thicknesses of at least 20 coatings from the best-developed carbonate horizon. For practical reasons, we have modified the method in two ways. First, we measure the thickness of coatings regardless of pebble lithology. Second, we average the data for pebbles taken from a 20-cm thick depth interval (for example, Figure 2). This allows one to excavate a soil pit in 10-cm depth increments, setting aside at least 10 pebbles from each depth increment. After the soil pit is 50 or 60 cm deep, we

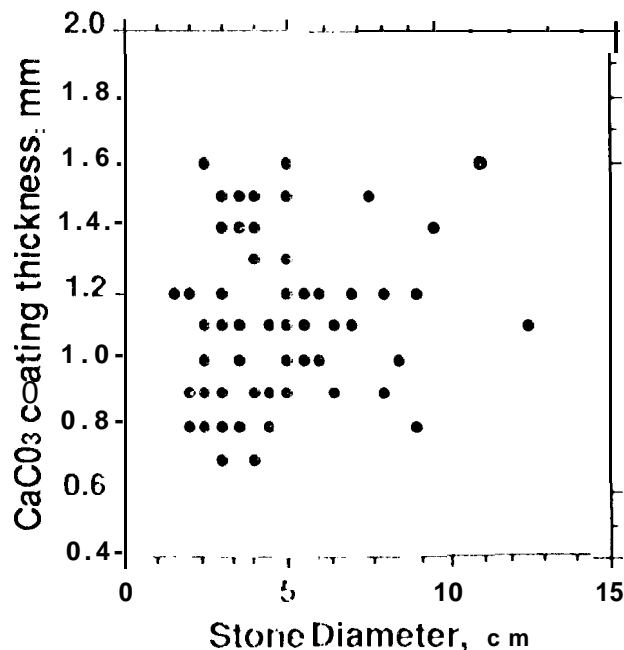


Figure 3. The thickness of calcium-carbonate pebble-bottom coatings plotted against the b-axis diameter of the stones hosting each coating. A correlation coefficient of 0.02 indicates that stone size does not explain the variance in coating-thickness values.

break the stones, measure the coating thicknesses, and generate a plot like Figure 3 in the field. Visual inspection of the plot reveals the location of the 20-cm thick horizon containing the thickest coatings or indicates whether the pit should be deepened and more data collected. For educational purposes, it is easiest to collect samples from stream-cut or road-cut exposures.

#### Reproducibility of Coating Thickness

When building a chronosequence, it is important to evaluate the reliability of the soil-development index. We evaluate the reliability of coating-thickness values below, using data from soils on the youngest alluvial fans in the study area. First, one should consider factors within the soil that might confound the results. For example, since the measurements were of pebble-bottom coatings, fine-textured soils containing less than 25% gravel by volume were avoided because of the different mode of carbonate deposition in those soils. We were also concerned that the size of a pebble might influence the thickness of its carbonate coating. This is not a problem as illustrated by Figure 3 where the data are for pebbles taken from the carbonate horizon of one soil. The thickness values are scattered but are not dependent on b-axis diameter within the range sampled, which was 2 to 15 cm.

Soils are rarely identical even in nearby soil pits. Because of this natural variability, we evaluated the at-a-site reproducibility of mean coating thickness by excavating four soil pits into the Willow Creek alluvial fan. The average of the four mean-thickness

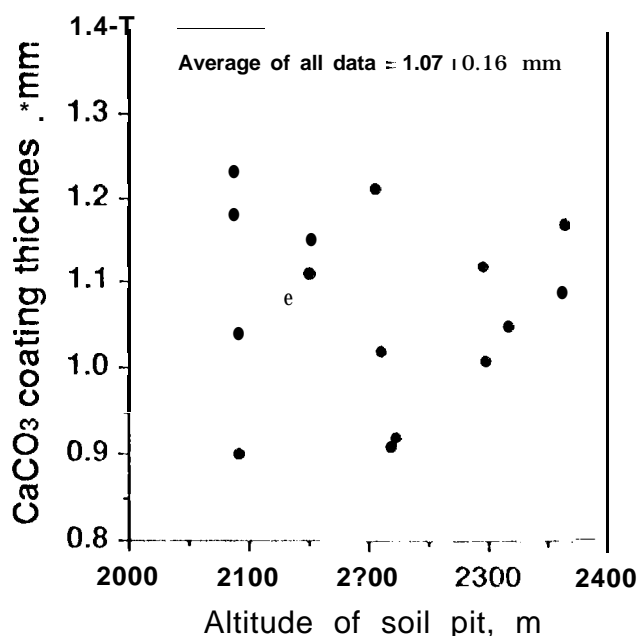


Figure 4. The mean thickness of calcium-carbonate pebble-bottom coatings plotted against the altitude of soil sampling sites. A correlation coefficient of 0.00 indicates that altitude explains none of the variance in mean coating-thickness.

values is 1.09 mm, and the range is 0.9 to 1.23 mm or 17%. Measurement of at-a-site variability is the easiest way to incorporate the subject of reproducibility into a field exercise.

Soils of one age also vary among sites because of differing micro-climate. This is evaluated using data from 16 soil pits on 8 late-glacial alluvial fans. The averaged coating thickness for these sites is 1.07 mm and the range about that average is  $\pm 0.16$  mm or 15%. The at-a-site variability is the same as the at-tr-site variability. The 1 G soil pits differ in altitude by as much as 275 m (900 feet), but, as shown on Figure 4, mean coating thickness does not depend on site altitude. At most of these sites, 80 to 100% of the pebbles within the soil are calcareous (limestone and dolomite), and within that limited range the thickness of coatings does not depend on parent material lithology. At one site, only 14% of the pebbles within the soil are calcareous, and the mean coating thickness is 0.92 mm—thin but still within the range of the other data. Specific micro-climate variables like annual precipitation cannot be evaluated, but we would caution against applying data from “dry” sites to the chronosequence presented here. Dry sites can be identified by 1) vegetation cover that is more sparse than that at the Willow Creek type locality, 2) the presence of prickly pear cactus, or 3) the presence of pedogenic gypsum deep in the soil. For field exercises elsewhere, use sites with similar vegetation for your chronosequence.

The final reproducibility issue is whether the results depend on the person making the observation, and this too can be easily incorporated into a field

exercise. We evaluated this using data in Pierce (1985) and Pierce and Scott (1982) for landforms along the Lost River fault between the towns of Mackay and Arco. The six coating-thickness values for the Ramshorn late-glacial alluvial fan average 1.15 mm with range of  $\pm 0.15$  mm or 13%. The average of data for five latest-glacial alluvial fans is 1.0 mm with range of  $\pm 0.2$  mm or 20%. Their results are essentially the same as ours. Given the considerations above, we conclude that mean coating-thickness values should be accurate to within 10 or 20% in the Lost River Valley.

### Age Constraints for Chronosequence

It is very unusual to find dateable material for a chronosequence, and isotopic dating is expensive. Therefore, teachers will most likely use soils as a tool for determining relative age based on the knowledge that carbonate coatings, like scale in a tea kettle, thicken with time. Nonetheless, it is instructive to see how numerical age constraints are incorporated into a chronosequence.

We were exceptionally fortunate to discover dateable material associated with a sequence of soils that are similar but differ in age. Each soil in the Lost River chronosequence (Table 1) has an age constraint (Table 2) as discussed below. It should be stated from the outset that it is impossible to determine the exact age of a soil, rather the scientist uses dateable material and geologic relationships to constrain the soil's age.

The ideal circumstance is to find charcoal or wood in a stratigraphic position that is clearly younger or older than a soil. For example, at the Elkhorn Creek site, dateable material was discovered with clear stratigraphic relationships to soils as illustrated on Figure 5. The site is close to the boundary of the SW and SE quarters of Section 26; T6 N, R22 E. Elkhorn Creek is incised into a prominent alluvial fan, and the parent material for three soils (E4, E3, and E1) are debris-flow deposits. These deposits consist of sandy to loamy gravel containing minimal amounts of silt and clay. The deposit of soil E4 is underlain by an organic horizon (a former soil surface) that contained wood sample A-5171, and the deposit of soil E3 is underlain by an organic horizon that contained charcoal sample A-5168a. The ages of the wood and charcoal samples are therefore maximum ages for the overlying soils. Sample A-5171 also provides a minimum age for the underlying deposit hosting soil E3. The parent material for soil E1 is a thick and extensive deposit resting on a black organic horizon with abundant charcoal (A-5167a) that yields a maximum age for that soil.

Stratigraphy also allowed us to understand the age relationships at Rock Creek (NW quarter of Section 3; T19 N, R22 E). The two Rock Creek soils (R1 and R2) are developed in a late Holocene terrace and are exposed in a stream-cut just upstream of the 1953 Borah Peak earthquake rupture trace. The fluvial deposits are sandy gravel with thin surface layers of silty sand. In the late Holocene, a channel was cut

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Soils of Lost River Chronosequence			
Soil	Mean coating thickness, mm	Age constraint	
		Radiocarbon sample #	Age relative to soil
R2	0.04	A-5172	maximum
R1	0.055	A-5172	maximum
E4	0.06	A-5171	maximum
E3	0.14	A-5168a	maximum
E3	0.14	A-5171	maximum
LG	0.37	w-4427	Close ?
E1	0.60	AA-4867	maximum
E1	0.60	A-5167a	maximum
Glacial Fans	1.077	see Table 2 and text for age ranges	
Glacial Moraine	1.4		

**Table 1.** Soils used in the Lost River, Idaho, chronosequence with soil identification and mean thickness of calcium-carbonate pebble-bottom coatings. See text for soil descriptions. Each soil has an age constraint (Table 2) that is a maximum (age estimate is older than soil), a minimum, or an estimated age range.

into the parent material of soil R1 and was subsequently filled with the parent material of soil R2. At the contact of the two deposits there is a silty sand layer from which charcoal sample A-5172 was taken. Therefore, the charcoal must be older than the younger soil R2 and younger than R1.

Crosscutting relationships can be used to help constrain the age of soils. For example, we used the crosscutting relationship of the Lost River fault to establish a minimum age for soil E1 at Elkhorn Creek (Figure 5). The parent material of soil E1 and the underlying black horizon can be traced to a location where they are displaced by the Thousand Springs segment of the Lost River fault. The soil surface was ruptured by the 1983 Borah Peak earthquake and the fresh 1983 fault scarp is located at the foot of an older, rounded fault scarp created by a prehistoric earthquake. The age of soil E1 can be constrained with knowledge of the age of the prehistoric earthquake, and that knowledge is based on data from a different site where both earthquakes ruptured a hillslope creating a closed depression. This hillslope site is located near Willow Creek in the NE quarter of Section 17; T 10 N, R 22 E. A trench excavated across the depression revealed charcoal (AA-4867) at the bottom of the sequence of colluvium filling the depression. That charcoal must be younger than the prehistoric earthquake, and the earthquake is younger than soil E1 (Vincent, in preparation). Because we have both minimum- and maximum-age constraints, soils E1 and E3 have very reliable ages.

Age Constraints for Lost River Chronosequence				
Laboratory sample #	Material	Conventional age (BP)	Calibrated age (BP)	Calibrated age 2 $\sigma$ range (BP)
A-5172	charcoal	490 $\pm$ 120	517 $\pm$ 0	664-294
A-5171	wood	915 $\pm$ 55	880 (1)	931-720
A-5168a	charcoal	1,180 $\pm$ 130	1,067 (1)	1,313-890
w-4427	organic matter	4,320 $\pm$ 130	4,862 (1)	5,242-4,643
AA-4867	charcoal	9,045 $\pm$ 100	9,994 (1)	10,223-9,857
A-5167a	charcoal	9,710 $\pm$ 240	10,954 (1)	11,950-10,279
Late-glacial alluvial fans		14,000 -- 15,000	16,700 -- 17,900 (2)	
Latest-glacial moraine		18,000 -- 20,000	21,400-23,500 (2)	

**Table 2.** Age constraints for Lost River chronosequence including all information important for future reference. The conventional ages are the dates provided by the laboratories, in radiocarbon years before present (BP), with analytical errors. These dates were calibrated to calendar years BP using (1) the program written by Stuiver and Reimer (1993) or (2) using data in Bard and others (1990). The 95% confidence intervals (2  $\sigma$ ) for calibrated ages are shown. The conventional age for sample W-4427 is from Scott and others (1985). The age range estimates (in radiocarbon years) for the latest glacial fans and moraine are from Pierce and Scott (1982).

Even when rare dateable material is discovered, the resulting age constraint may be less than ideal. For example, the age of the most recent earthquake on the Mackay segment of the Lost River fault helps indicate the age of a soil. Scott and others (1985) report a maximum age for this earthquake based on fault-trench studies where a sample (W-4427) of "organic matter buried by colluvium derived from" the fault scarp created during the youngest earthquake. We have studied the soils on many fans and terraces displaced by this event. The youngest terrace faulted by only this earthquake is a fluvial surface at a site informally named "long gulch" (LG). The site is southwest of Mount McCaleb at the boundary of the NE and SE quarters of Section 32; T 8 N, R 23 E. We believe the ages of the soil (LG) and the organic matter (W-4427) are quite close, but, because both are older than the earthquake, the true age of the soil is uncertain.

When dateable material cannot be found, age estimates must be

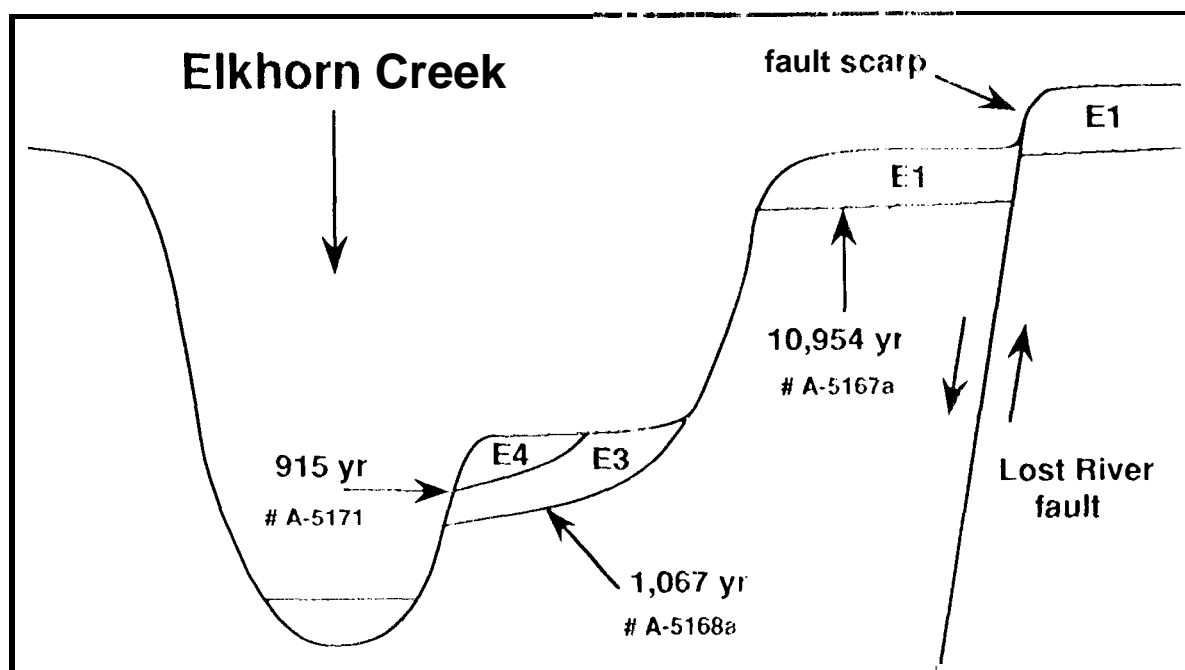


Figure 5. Idealized cross section of Elkhorn Creek showing soils E1, E3, and E4 and the location of dated charcoal or-wood between deposits. The ages indicated are calendar years before present. The crosscutting relationship of soil E1 and the Lost River fault is also shown. The fault ruptured in 1983 and also just prior to ten-thousand years ago.

based on inference. For example, age ranges have been estimated for the prominent late-glacial alluvial fans and glacial moraines in the study area by Pierce and Scott (1982) and Pierce and Colman (1986). Their age ranges are not based on dateable material found in the study area, rather they are estimates based on regional correlation, deductive reasoning, and corroborative evidence. We use their age range of 14,000 to 15,000 years BP (radiocarbon years before present) for the late-glacial alluvial fans, and the age of full-glacial time (18,000–20,000 years BP) is assumed for latest-glacial moraines (Table 2). For the late-glacial alluvial fans, the coating thickness of 1.07 mm on Table 1 is the average of data from eight alluvial fans. The coating thickness of 1.4 mm is from a soil at the foot of the latest-glacial terminal moraine at Cedar Creek (NW quarter of Section 10; T 9 N, R 22 E).

The last issue involves the meaning of radiocarbon ages. Isotope laboratories report radiocarbon ages based on a calculation that embodies the assumption that the  $^{14}\text{C}$  content in atmospheric  $\text{CO}_2$  has been constant, but this assumption is not strictly true (Stuiver and Reimer, 1993). The result is a nonlinear distortion in the  $^{14}\text{C}$  time scale. Fortunately, radiocarbon ages can be converted into calendar years, and we have made this conversion for all age constraints on Table 2. Radiocarbon ages younger than about 10,000 years can be calibrated using tree-ring chronologies. The best available means of calibrating older ages utilizes paired measurements of uranium/thorium and radiocarbon in corals (Bard and others, 1990).

## Results and Conclusions

The resulting Lost River chronosequence is illustrated on Figure 6. The thickness of pedogenic calcium-carbonate pebble-bottom coatings increases progressively with time. Because of past changes in climate and other factors, soil properties do not necessarily change linearly with time (Machette, 1985). The thickening rate for pebble-bottom coatings in the study area appears to have ranged between 1.1 and 0.4 mm/10 ky (millimeters per ten thousand years). The average thickening rate, however, over the past 10,000 years is 0.56 mm/10 ky and is about 6 or 7  $\times 10^{-5}$  mm/y for the past 25,000 years or so. These results are quite close to the long-term average thickening rate of  $6 \pm 1 \times 10^{-5}$  mm/y calculated by Pierce (1985) for time periods of 30,000 to 160,000 years. Pierce's rates are based on uranium/thorium isochron ages of individual layers within carbonate coatings from 61 soils in the Lost River Valley.

Chronosequences can be used in three ways. First, chronosequences can be used to increase our understanding of the processes that form soils. For example, the highest rate at which coatings thicken has occurred during the past 1,000 years (Figure 6), but this cannot be easily explained by what is known about Holocene climates (Davis and others, 1986; Beiswenger, 1991; Whitlock, 1993). One plausible explanation, and a concept not yet discussed in the literature, is based on the following observations. First, most older alluvial deposits are now high and dry, completely abandoned by down-stream incision. This means that moisture for soil-forming processes

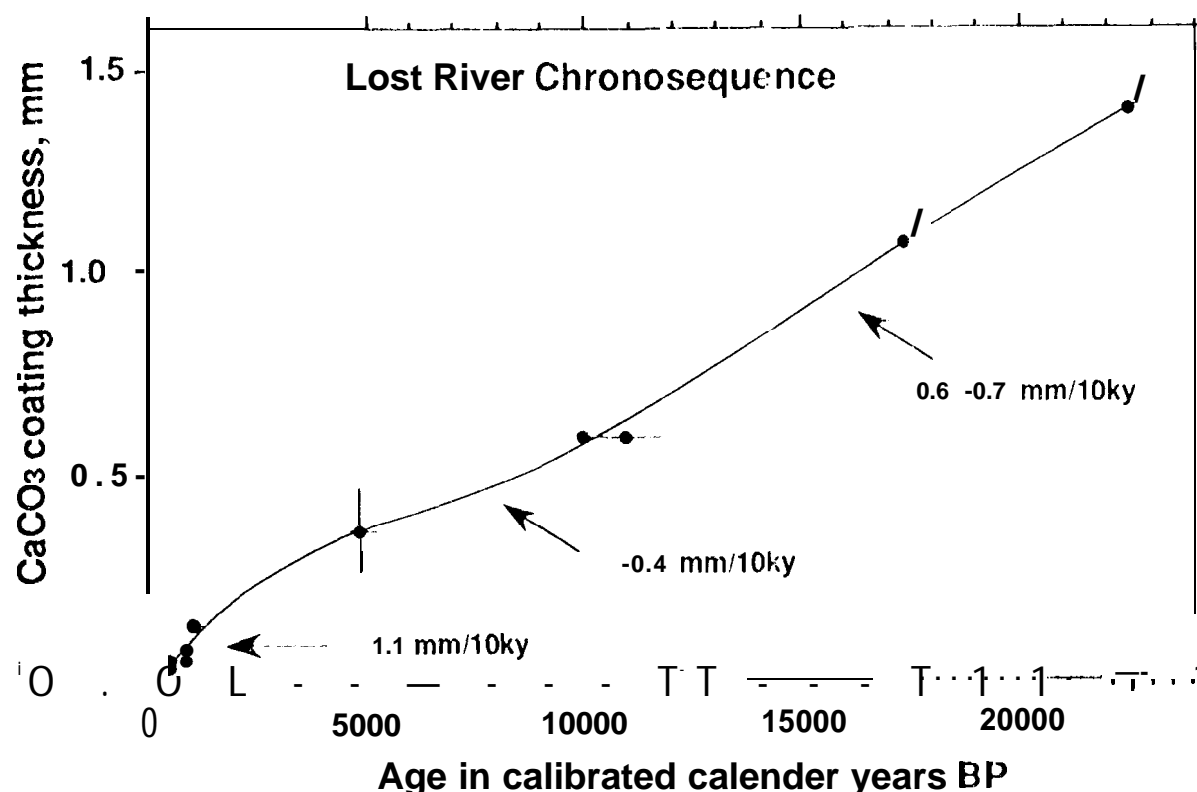


Figure 6. Mean thickness of pedogenic carbonate pebble-bottom coatings plotted against the age of soils in the Lost River Valley, Idaho. The rates at which coats thicken (the slope of the line) are labeled in millimeters per ten thousand years (mm/10 ky).

is derived solely from rain or snow falling directly on the surface. In contrast, young stream terraces may be only partially abandoned because they are often only slightly incised by the stream that formed them. If so, the deposits occasionally receive moisture from overbank flooding that should increase rates of soil formation compared to sites not subject to flooding. The deposits containing soils R2, R1, F4, and F3 are only slightly incised by nearby streams, and these are the soils that indicate that the rate of thickening of coatings has been most rapid during the past 1,000 years.

Chronosequences can be used as a tool to establish regional correlation of landforms and the timing of regional phenomena, such as climate change. For example, along the Mackay segment of the Lost River fault there are numerous small alluvial cones emanating from small, steep watersheds on the range front. The alluvial cones have soils with rather consistent carbonate-coating thicknesses that average 0.73 with range of  $\pm 0.2$  mm. Applying that coating thickness to Figure 6 indicates that the deposits are about 12,000 years old. Although not comparable in magnitude to the major episodes of gravel deposition (Pierce and Scott, 1982), they represent the last Pleistocene episode of gravel deposition. Paleobotanists have shown that about 12,000 years ago the climate of the area was in transition; it had been cold but transformed into the warm and dry conditions of the early Holocene (Davis and others, 1986; Beiswenger, 1991; Whitlock, 1993).

Lastly, chronosequences can be used to establish the age of local events such as faulting. Along the Mackay segment of the Lost River fault, the youngest earthquake occurred about 5,000 years ago, but the age of the next oldest earthquake is unknown. This earlier earthquake ruptured the surface of prominent late-glacial alluvial fans (Table 1) but did not rupture the surface of the small alluvial cones mentioned above. This indicates the earthquake occurred sometime between 12,000 and 17,000 years ago.

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#### References Cited

- Bachman, G.O., and Machette, M. N., 1977, Calcic soils and calcretes in the southwestern United States: U.S. Geological Survey Open-File Report 77-794, 162p.
- Bard, E., Hamelin, B., Fairbanks, R. G., and Zindler, A., 1990, Calibration of the  $^{14}\text{C}$  timescale over the past 30,000 years using mass spectrometric U-Th ages from Barbados corals: *Nature*, v. 345, p. 405-410.
- Beiswenger, J. M., 1991, Late Quaternary vegetational history of Grays Lake, Idaho: *Ecological Monographs*, v. 61, p. 165-182.



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- Birkeland, P.W., 1984, *Soils and geomorphology*: New York, Oxford University Press, 372 p.
- Birkeland, P.W., 1990, Soil geomorphic analysis and chronosequences - A selective overview, in Knuepfer, P.L.K., and McFadden, L.L.), eds., *Soils and landscape evolution*: Geomorphology, v. 3, p. 207-224.
- Bull, W.B., 1991, *Geomorphic Responses to Climatic Change*: New York, Oxford University Press, 326 p.
- Chadwick, O. A., Brimhall, G.H., and Hendricks, I. M., 1990, From a black to a gray box - A mass balance approach to understanding processes, in Knuepfer, P.L.K., and McFadden, L.L.), eds., *Soils and landscape evolution*: Geomorphology, v. 3, p. 369-390.
- Davis, O.K., Sheppard, J. C., and Robertson, S., 1986, Contrasting climatic histories for the Snake River Plain, Idaho, resulting from multiple thermal maxima: *Quaternary Research*, v. 26, p. 321-339.
- Gilt, L.H., Peterson, F.F., and Grossman, R.B., 1966, Morphological and genetic sequences of carbonate accumulation in desert soils: *Soil Science*, v. 101, p. 347-360.
- Harden, J. W., 1982, A quantitative index of soil development from field descriptions: examples from a chronosequence in central California: *Geoderma*, v. 28, p. 1-28.
- Jenny, H., 1941, *Factors of soil formation*: New York, McGraw-Hill, 281 p.
- Klappa, C.F., 1979, Calcified filaments in Quaternary calcretes: Organo-mineral interactions in the vadose subaerial environment: *Journal of Sedimentary Petrology*, v. 49, p. 955-988.
- Machette, M. N., 1978, Dating Quaternary faults in southwestern United States using buried calcic paleosols: *U.S. Geological Survey Journal of Research*, v. 6, p. 369-381.
- Machette, M. N., 1985, Calcic soils of the southwestern United States, in Weide, D.L., and Faber, M. I., eds., *Soils and Quaternary Geology of the Southwestern United States*: Geological Society of America Special Paper 203, p. 1-21.
- McFadden, L.D., Amundson, R. G., and Chadwick, O. A., 1991, Numerical modeling, chemical, and isotopic studies of carbonate accumulation in soils of arid regions, in Occurrence, characteristics, and genesis of carbonate, gypsum, and silica accumulations in soils: *Soil Science Society of America Special Publication* 26, p. 17-35.
- Phillips, S., Milnes, A.L., and Forster, R. C., 1987, Calcified filaments: An example of biological influences in the formation of calcrete in south Australia: *Australian Journal of Soil Science*, v. 25, p. 405-477.
- Pierce, K.L., and Scott, W. E., 1982, Pleistocene episodes of alluvial-gravel deposition, southeastern Idaho, in Bonnicksen, B., and Breckenridge, R.M., eds., *Cenozoic Geology of Idaho*: IBMG Bulletin 26, Moscow, ID, Idaho Bureau of Mines and Geology, p. 685-702.
- Pierce, K.L., 1985, Quaternary history of faulting on the Arco segment of the Lost River fault, central Idaho, in Stein, R. S., and Bucknam, R. C., eds., *Proceedings of Workshop XXVIII on the Borah Peak, Idaho Earthquake*, U. S.G.S. Open-File Report 85-290, p. 195-203.
- Pierce, K. I., and Colman, S. M., 1986, Effect of height and orientation (microclimate) on geomorphic degradation rates and processes, late-glacial terrace scarps in central Idaho: *Geological Society of America Bulletin*, v. 97, p. 869-885.
- Quade, J., Cerling, T. R., and Bowman, J.R., 1989, Systematic variations in the carbon and oxygen isotopic composition of pedogenic carbonate along elevation transects in the southern Great Basin, United States: *Geological Society of America Bulletin*, v. 101, p. 464-475.
- Reheis, M.C., Sowers, J.M., Taylor, E.M., McFadden, L.L.), and Harden, J. W., 1992, Morphology and genesis of carbonate soils on the Kyle Canyon fan, Nevada, USA: *Geoderma*, v. 52, p. 303-342.
- Scott, W.E., 1982, *Surficial geologic map of the eastern Snake River Plain and adjacent areas*, 111 to 115 W., Idaho and Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map 1-1372.
- Scott, W.E., Pierce, K.L., and Hait, M.H., Jr., 1985, Quaternary tectonic setting of the 1983 Borah Peak earthquake, central Idaho: *Bulletin of the Seismological Society of America*, v. 75, p. 1053-1066.
- Stuiver, M., and Reimer, P.J., 1993, Radiocarbon calibration program revision 3.0.3: *Radiocarbon*, v. 35, p. 215-230.
- Vincent, K.R., and Chadwick, O. A., 1994, Synthesizing bulk density for soils with abundant rock fragments: *Soil Science Society of America Journal*, v. 58, p. 455-464.
- Whitlock, C., 1993, *Postglacial vegetation and climate of Grand Teton and southern Yellowstone National Parks*: *Ecological Monographs*, v. 63, p. 173-198.

## About the Authors

The authors contribute frequently to less accessible scientific literature but, as illustrated with this article, they are motivated to convey the fruits of their research to their students and to other teachers.

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